A Direct Simulation-Based Study of Radiance in a Dynamic Ocean

Lian Shen
Department of Civil Engineering
Johns Hopkins University
Baltimore, MD 21218
phone: (410) 516-5033 fax: (410) 516-7473 email: LianShen@jhu.edu

Award Number: N00014-06-1-0073

LONG-TERM GOAL

The primary focus of this research is to integrate dynamical processes of wave and turbulence in the upper ocean surface boundary layer (SBL) into a physics-based computational capability for the time-dependent radiative transfer (RT) in the ocean. The combined capability we develop will provide direct forward predictions of the radiance distributions in the upper ocean. We aim to use this capability for understanding the basic features and dependencies of oceanic radiance on the wave environment, to provide guidance and cross-calibration for field measurements, and to validate and benchmark existing and new theories. As an ultimate goal, the proposed direct simulation also provides a framework, in conjunction with sensed radiance data, for the optimal reconstruction of salient features of the ocean surface and the above-water scene.

OBJECTIVES

This project is part of the modeling effort in the Radiance in a Dynamic Ocean (RaDyO) DRI. The scientific and technical objectives of our research are to:

- develop numerical capabilities for the direct simulation of nonlinear capillary-gravity waves (CGW) with the inclusion of wave breaking dissipation, energy input by wind, and surfactant effects

- develop numerical capabilities for free-surface turbulence (FST) and resultant surface roughness

- develop bubble transport simulation in CGW-FST field, with bubble source models using simulations of steep breaking waves and measurement data

- develop direct simulations of RT in the presence of SBL processes of wave, turbulence, and bubbles

- obtain validations and cross-calibrations against field measurements

- use numerical tools of forward prediction to understand and characterize the radiance distribution in terms of the SBL dynamical processes, and to parameterize and model radiance transport and distributions

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2008**	2. REPORT TYPE	3. DATES COVERED **00-00-2008 to 00-00-2008**
4. TITLE AND SUBTITLE **A Direct Simulation-Based Study of Radiance in a Dynamic Ocean**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Johns Hopkins University,Department of Civil Engineering,Baltimore,MD,21218**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**7**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

- develop inverse modeling for the reconstruction of free-surface properties and objects using measured RT data and direct simulation

APPROACH

We develop a simulation approach based on direct physics-based simulations and modeling to solve the problem of ocean RT in a dynamic SBL environment that includes CGW, FST roughness, wave breaking and bubble generation and transport. The complex dynamic processes of the ocean SBL, the nonlinear CGW interactions, the development and transport of FST, and the generation and transport of bubbles are modeled using physics-based computations. The modeling of these hydrodynamic processes is coupled with the computation of radiative transfer.

For the nonlinear gravity-capillary wavefield evolution, we employ an efficient phase-resolved computational approach. With this approach, we obtain detailed spatial and temporal information of the wavefield during its nonlinear evolution. This computational tool is based on an efficient high-order spectral (HOS) method that we developed for direct simulations of nonlinear gravity wavefield evolution. HOS is a pseudo-spectral method developed based on the Zakharov equation and mode-coupling idea. Using direct efficient HOS computations and sensed wave data, we can obtain a phase-resolved reconstruction of nonlinear wavefield evolution based on multi-layer optimizations. With this highly efficient approach, we expect to capture realistic ocean gravity and capillary wavefield that has a wide range of length scales.

In addition to CGW, radiative transfer at ocean surface is also affected by surface roughness associated with FST. In this study, for moderate wave amplitudes, the FST field is obtained from simulation of the Navier-Stokes equations on a boundary-fitted grid subject to the fully-nonlinear free-surface boundary conditions. When waves steepen and break, an interface capturing method on fixed Eulerian grids is used, with which the air and water together are treated as a system with varying density, viscosity, and diffusivity. Effects of surfactants can be captured through the Plateau-Marangoni-Gibbs effect for which we perform direct simulation of the surfactant transport in the free-surface flow, which is in turn affected by the surfactant-laden boundary conditions. To capture the interaction between FST and CGW, we will perform FST simulations with realistic wave inputs obtained from the HOS CGW simulations.

The high-resolution mapping of the free-surface deformation from our direct CGW and FST calculations is coupled into the computation of the underwater radiance field. As light enters the water from the air, they are modified in both propagation direction and intensity at the sea surface subject to Snell’s law and Fresnel transmission. The propagation of radiance in the sea water is captured by simulation of radiative transport subject to absorption and multiple scattering. In this study we perform direct simulations of RT in a three-dimensional, temporally-evolving, upper-ocean environment with the key SBL processes being directly simulated. We will first focus on a Monte Carlo simulation of photons while other techniques for the direct simulation of radiance will be investigated at a later stage of this project. In order to capture radiative scattering by bubbles which are generated by wave breaking, we first simulate transport of bubbles by tracking Lagrangian trajectories and by computations with an Eulerian multi-phase fluid modeling. Based on the simulated locations and populations of bubbles with various size distributions, scattering of radiance is solved numerically using the radiative scattering result of individual bubbles obtained with the Mie theory.

Large-scale high-performance computation on parallel computers is used to meet the computational challenges in the CGW, FST, and RT simulations. The suite of codes developed for this research is parallelized using massage passing interface (MPI) based on domain decomposition.

WORK COMPLETED

Research performed during the fiscal year of 2008 includes:

- Investigation of the interaction between surface waves and ocean turbulence and the effect on underwater radiative transfer
- Investigation of dependence of underwater radiative transfer on the dynamics of wave steepening and breaking
- Investigation of realistic, developing seas subject to wind-wave dynamic two-way coupling, and the effect on underwater radiative transfer
- Simulation and analysis of underwater irradiance time signal and comparison with measurement data in the literature
- Initial study of measurement data
- Investigation of reverse modeling of sea surface geometry based on the underwater light field and wave dynamics

RESULTS

Radiative transfer in the upper ocean depends largely on the sea surface geometry, for which surface wave and turbulence are the two dominant fluid flow processes. Wave and turbulence are strongly coupled with each other. Turbulence is generated by wave evolution process including wave breaking, and is affected by the passage of waves. Waves, on the other hand, are distorted and dissipated by turbulence. In the study, we have developed an advanced numerical approach for the simulation of wave-turbulence interaction. Figure 1 shows a representative result, in which an originally smooth progressive wave encounters an ocean turbulence field. The surface roughness caused by the turbulence, the generation of small waves, as well as the distortion of the dominant wave is clearly shown.

For several sea conditions with steep and breaking waves, we have developed a simulation capability based level-set and volume-of-fluids methods. Figure 2 shows a simulation result for steepening and breaking of surface waves caused by very strong ocean turbulence. Our simulation of radiative transfer shows that the underwater light field is significantly affected by the wave breaking process. Combination of our numerical tool with the measurement data to obtain realistic sea conditions in the simulation will be a focus of our research at the next step.

In order to obtain realistic wavefield under the action of winds, it is desirable to capture the wind-wave interaction in the simulation. For the first time, we have recently achieved the phase-resolving simulation of the nonlinear evolution of irregular broadband wavefield with two-way dynamic coupling between wind and waves. Figure 3 shows a typical result. Armed with this numerical capability, we have investigated the radiance signal under the waves. Figure 4 shows the time signal of irradiance at underwater probes. The appearance of short-duration, large-magnitude spikes agrees with field measurement.

Figure 5 shows preliminary results on reverse modeling. Using the radiance field under an irregular wave field, we try to reconstruct the sea surface geometry. As the depth of available radiance data increases, the quality of reverse modeling decreases as expected. On the other hand, it is not that the closer to the surface the better. There exists an optimum depth where effects of both the dominant large waves and the small waves/surface roughness are captured. In this study we intend to develop a framework for the integration of wave-turbulence simulation, radiative transfer simulation, data assimilation, and optimization to achieve reverse modeling, which is a subject of our on-going research.

IMPACT/APPLICATION

This study aims to obtain a fundamental understanding of time-dependent oceanic radiance distribution in relation to dynamic SBL processes. Our work is intended as part of an overall coordinated effort involving experimentalists and modelers. The simulation capabilities developed in our research will provide experimentalists with a powerful tool to validate the observation data. The simulation tool is expected to provide some guidance for field measurement planning. The simulation can also provide whole-field (spatial and temporal) data that helps the interpretation of sparse observation datasets. From simulation, some physical quantities that are difficult to measure can be obtained. What is also significant is that the simulation can be used as a useful tool to isolate physical processes that are coherent in the natural environment. With such analysis, improved understanding, modeling and parameterizations of dependencies of oceanic radiance on SBL environment will be obtained. Our ultimate goal is to use the forward modeling capabilities resulted from this project as a framework for inverse modeling and reconstruction of ocean surface and above water features based on sensed underwater radiance data.

TRANSITIONS

The numerical datasets obtained from this project will provide useful information on physical quantities difficult to measure. Simulations in this study will provide guidance, cross-calibrations and validations for the experiments. They also provide a framework and a physical basis for the parameterization of oceanic radiative transfer in relation to dynamic surface boundary layer processes.

RELATED PROJECTS

This project is part of the ONR-sponsored Radiance in a Dynamic Ocean (RaDyO) DRI (http://www.opl.ucsb.edu/radyo). Our study is performed jointly with Professor Dick K.P. Yue’s group at MIT and is in close collaboration with other investigators in this DRI.

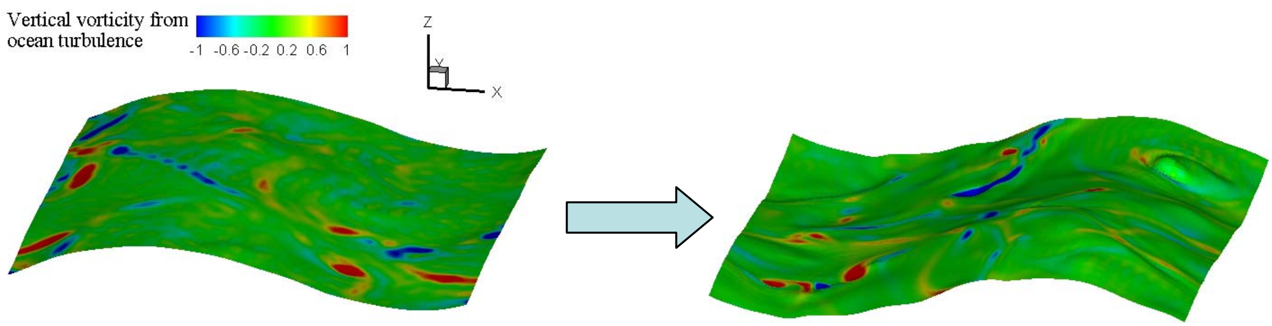

Figure 1. Interaction of surface wave with turbulence. Plotted are surface elevation of the wave and distributions of vertical vorticity at the sea surface at early (left) and late (right) stages.

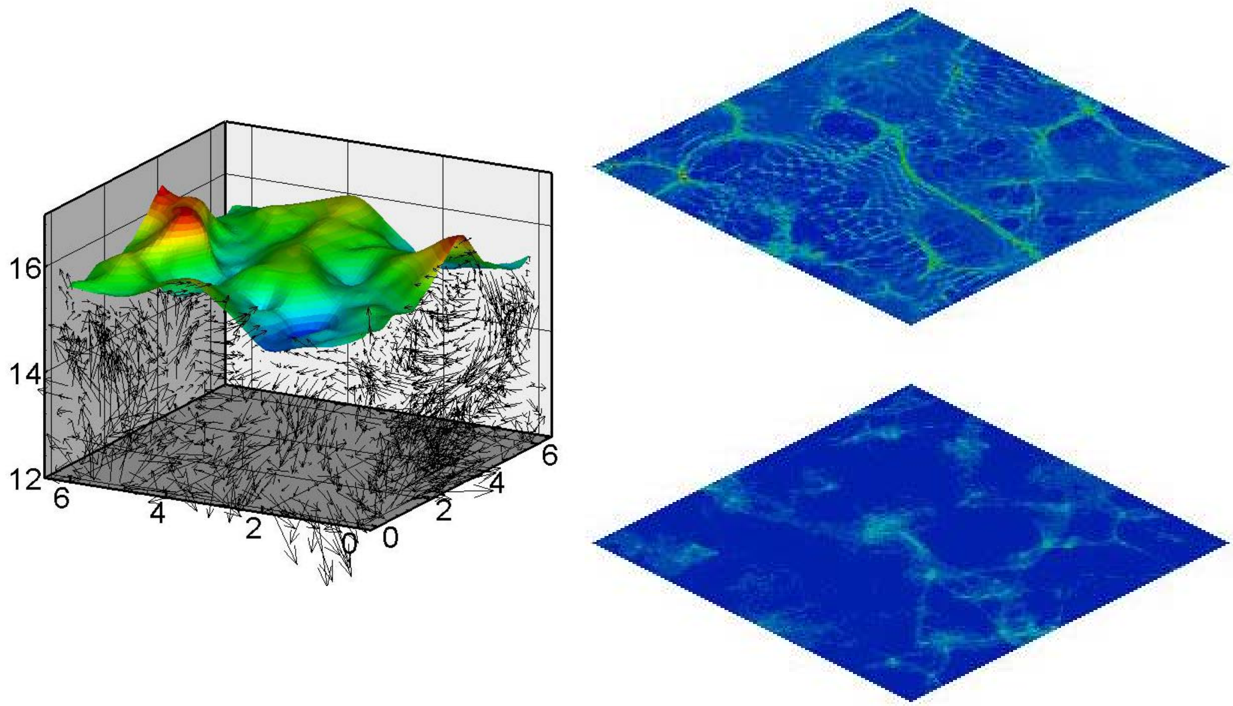

Figure 2. Left: simulation results of steep/breaking waves. Plotted are surface elevation and the flow velocity vectors underneath. Right: distribution of irradiance field at two representative depths.

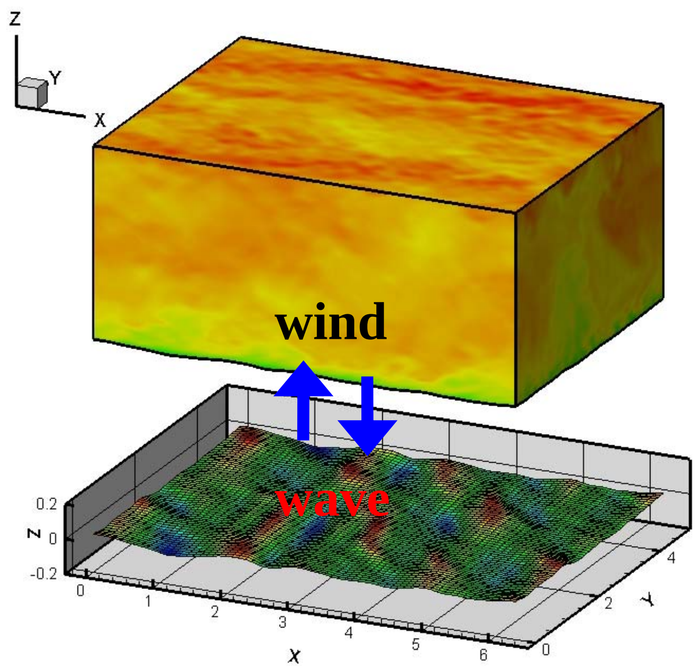

Figure 3. Sea surface geometry obtained from wind-wave coupled simulation. Plotted are instantaneous wind and wave fields.

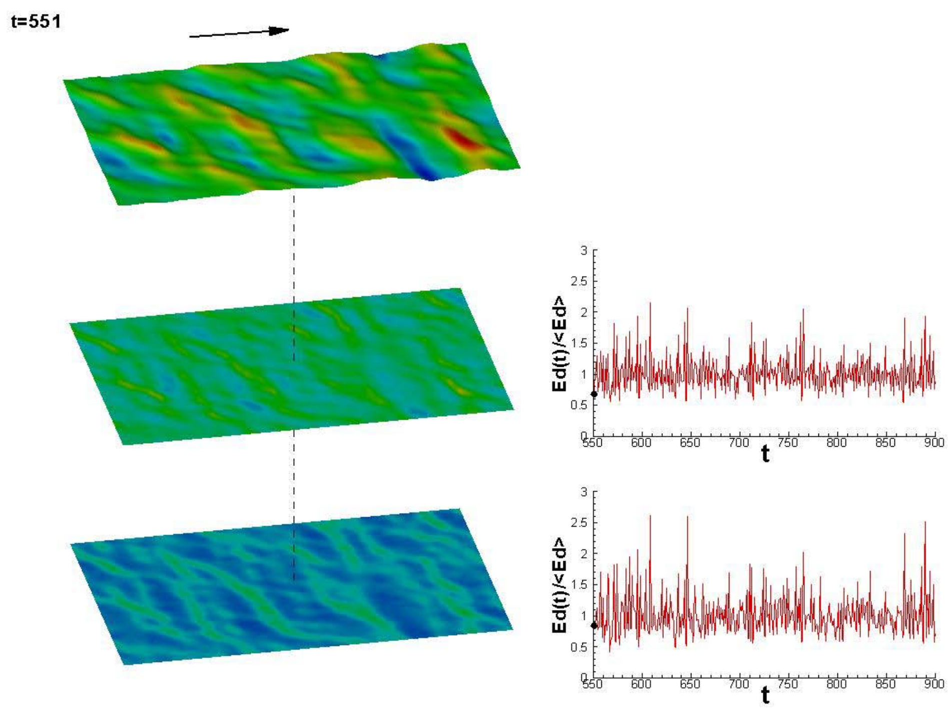

Figure 4. Left: instantaneous surface water profiles obtained from wind-wave simulation and underwater irradiance distributions at two different depths. Right: time history of irradiance intensity at the points marked on the left figures.

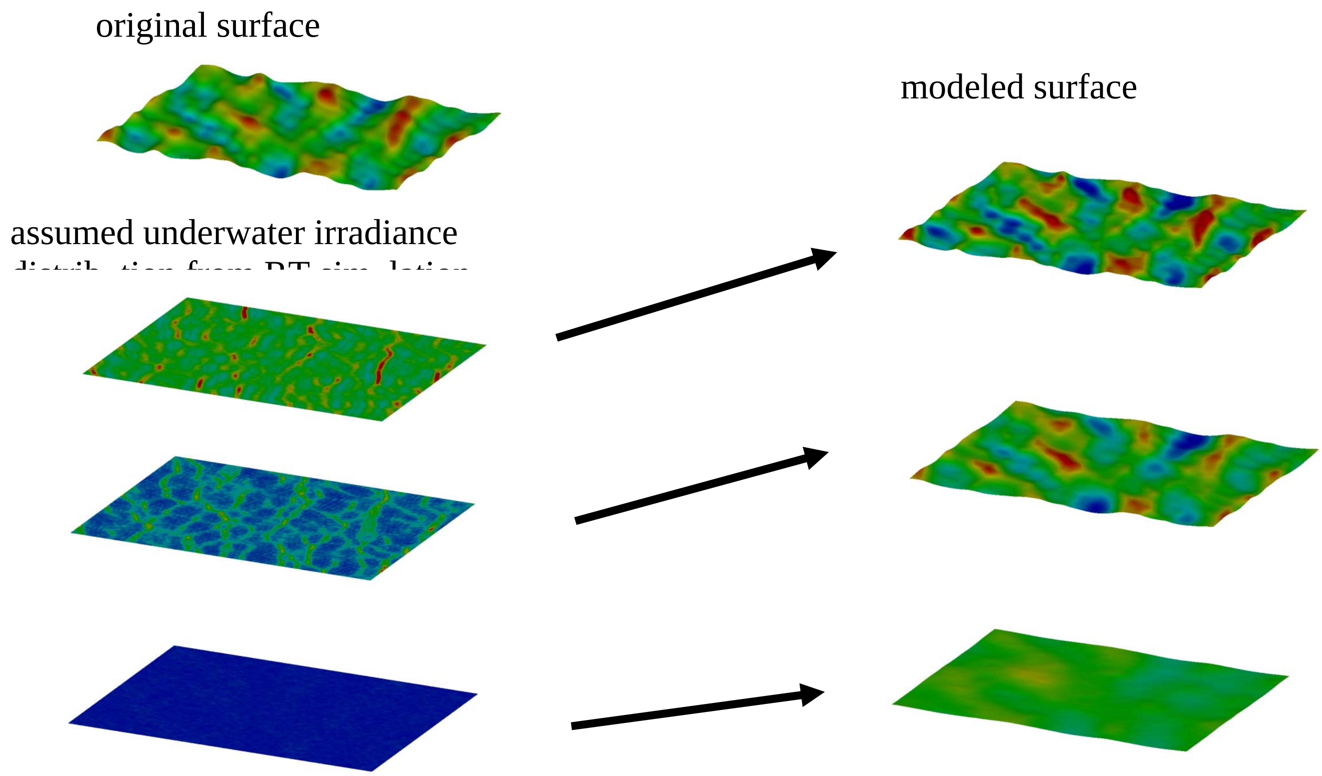

Figure 5. Reconstruction of water surface geometry based on underwater irradiance field at different depths. Left: the true water surface elevation and distribution of irradiance field at various depths. Right: reconstructed surfaces using underwater irradiance data.